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Integrated Use of Biochar, Hydrogels, and Manure Improves Green Gram (*Vigna radiata*) Productivity in Kwale County, Kenya

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

Land degradation, low soil fertility, limited moisture retention and climate variability continue to constrain green gram (*Vigna radiata* L.) production in smallholder farming systems in coastal Kenya. This study evaluated the effects of biochar, farmyard manure and Hydrogel on soil fertility, soil moisture, crop growth and grain yield of green gram under farmer-managed conditions in Kwale County, Kenya. Field experiments were conducted in Matuga, Lunga Lunga, Msambweni and Shimba Hills using a randomised complete block design with three replications. Treatments consisted of biochar at 10 t ha^{-1}, farmyard manure at 10 t ha^{-1}, Hydrogel at 5 kg ha^{-1} and an untreated control. Data were collected on soil moisture, soil organic carbon, total nitrogen, pH, exchangeable phosphorus, potassium and sulphur, plant height and grain yield. Analysis of

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variance was performed in R, and treatment means were separated at the 5% significance level. Biochar and farmyard manure generally produced the greatest improvements in soil fertility and crop performance. Biochar increased soil moisture, soil organic carbon, total nitrogen, pH and exchangeable phosphorus by 35%, 34%, 49%, 12% and 153%, respectively, compared with the control. Farmyard manure increased the same parameters by 33%, 28%, 36%, 11% and 133%, respectively. Hydrogel produced moderate improvements, particularly in soil moisture. Grain yield increased by 43% under biochar, 36% under farmyard manure and 20% under Hydrogel relative to the control.

Keywords: Green gram; Vigna radiata; biochar; Hydrogel; farmyard manure; soil moisture; soil organic carbon; soil fertility; grain yield; coastal Kenya.

1. Introduction

Green gram (*Vigna radiata* L.) is an important, highly nutritious grain legume widely cultivated in semi-arid and coastal regions because of its short growth cycle and ability to improve soil health (Food and Agriculture Organization, 2021; Esilaba et al., 2021a; Muchomba et al., 2023a). In Kenya, particularly in eastern and coastal counties, green gram contributes significantly to household food security, nutrition, income generation and livelihoods among smallholder farmers (Ministry of Agriculture, Livestock and Fisheries [MoALF], 2015; Muchomba et al., 2023a; Omar et al., 2023). Despite the crop's importance, its productivity in these regions has consistently remained low (0.5–0.8 t ha^{-1}), below the attainable yield of 1.5–2.0 t ha^{-1}, demonstrating a substantial productivity gap (Nair et al., 2019; Muchomba et al., 2023a).

The major factors limiting green gram production in major growing regions include declining soil health, poor agronomy, limited awareness and adoption of new technologies, as well as climate change-related effects such as unpredictable rainfall and land degradation (Esilaba et al., 2021b; Muchomba et al., 2023a). Coastal soils are largely characterised by a sandy texture and low organic matter content, with low water- and nutrient-holding capacity (Osuji et al., 2002; Kazungu et al., 2023). These conditions are further intensified by climate variability, which negatively affects rainfall reliability in rain-fed small-scale agricultural systems (Intergovernmental Panel on Climate Change, 2022), necessitating sustainable climate-smart agricultural practices.

Among the promising climate-smart agricultural practices are soil health management technologies such as biochar, hydrogels and organic manure (Adamtey et al., 2025; Ashraf et al., 2023; Waheed et al., 2026). Biochar, a carbon-rich material produced through the pyrolysis of organic biomass, has been reported to improve soil health, aggregation and water-holding capacity (Agegnehu et al., 2017; Khan et al., 2024; Pandian et al., 2024). Hydrogels function as highly specialised superabsorbent polymers capable of absorbing and gradually releasing large quantities of water in response to osmotic root demands, thereby reducing short-term moisture stress while maximising nutrient and water-use efficiency (Park et al., 2025; Kareem et al., 2026). Organic manure, on the other hand, improves soil physical, chemical and biological properties by supplying nutrients, stimulating microbial activity and enhancing soil physical attributes (Brady & Weil, 2016). Although biochar, hydrogels and farmyard manure have shown potential to improve soil productivity in other regions, comparable evaluations of these amendments under farmer-managed conditions in coastal agroecosystems remain limited. Recent studies outside the study area also show that biochar-based and organic amendments can increase available nitrogen, phosphorus, potassium and sulphur, and can improve soil physical and hydrodynamic characteristics (Banu & Rani, 2025; Dayoub et al., 2025). Systematic evidence also indicates that biochar can improve nutrient cycling and crop yield in sandy-textured soils, while superabsorbent hydrogels can improve soil hydro-physical properties and water-use efficiency under deficit irrigation (Bekchanova et al., 2024; Abdelghafar et al., 2024). Information on site-specific performance of biochar, Hydrogel and farmyard manure as separate amendments under farmer-managed green gram production in the sandy coastal soils is however limited. This study therefore assessed the effects of biochar, hydrogels and manure on soil moisture retention, nutrient retention and green gram (*Vigna radiata*) productivity in Kwale County, Kenya. The findings are expected to contribute to sustainable soil health management strategies for improving green gram productivity, soil moisture management and the resilience of smallholder farming systems in coastal agroecological zones.

2. Material and Methods

2.1 Site Description

The study was conducted on farmers' fields in Matuga, Lunga Lunga, Msambweni and Shimba Hills sub-counties of Kwale County, Kenya. These sub-counties lie within lowland agro-ecological zone three (CL3), at an altitude of 42–47 metres above sea level, between latitudes 4.47° S and 4.55° S and longitudes 39.13° E and 39.48° E (Jaetzold et al., 2012). The area experiences a bimodal rainfall pattern with two distinct seasons, namely March to July and October to December. Annual rainfall ranges from 1,000 to 1,200 mm, while average annual temperatures range between 24°C and 26.6°C.

2.2 Experimental Layout, Design and Crop Husbandry

The experiment was laid out in a randomised complete block design (RCBD) with four treatments and three replications. The treatments comprised biochar, Hydrogel, farmyard manure (FYM) and an untreated control. The treatments were applied during crop establishment at rates of 10 t ha^{-1} (biochar), 5 kg ha^{-1} (Hydrogel) and 10 t ha^{-1} (FYM).

The green gram variety Biashara was established at a spacing of 45 cm by 15 cm in experimental plots measuring 3 m by 3 m, resulting in a plant population of 133 plants per plot. Starter nitrogen and phosphorus were uniformly applied to all plots at rates of 10 kg N ha^{-1} and 20 kg P_2O_5 ha^{-1}. All recommended agronomic practices, such as thinning, weeding, and pest and disease control, were carried out uniformly across all treatments throughout the growing period.

2.3 Soil and Crop Data Collection

Data collected included initial soil attributes, crop growth and yield parameters. Initial soil attributes were evaluated by randomly collecting 15 soil cores per site at depths of 0–20 cm and 20–40 cm using a systematic sampling procedure. The samples were then composited into one sample for physical and chemical analysis. At the end of each cropping season, five cores were collected from the root zone of randomly selected plants within each plot at depths of 0–20 cm and 20–40 cm. The cores were mixed, and a 1 kg composite sample was packed for physicochemical analysis. The soils were analysed for moisture content, pH (water), total nitrogen (N), exchangeable phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), zinc (Zn), iron (Fe), manganese (Mn), copper (Cu) and sodium (Na). The analysis was carried out following the procedures described by Okalebo et al. (2002).

Five plants were randomly tagged from the middle rows of each plot 14 days after emergence and used for data collection throughout the experimental period. Data collected included plant height, number of leaves, pods per plant, days to 50% flowering, days to 50% pod formation, 100-grain weight and grain yield. Plant height was evaluated by measuring the height of the tagged plants from the soil surface to the apical meristem using a ruler on a weekly basis from two weeks after emergence until physiological maturity. Leaf development was evaluated by counting all leaves from the five tagged plants from one week after emergence on a weekly basis until physiological maturity. The number of pods per plant and the number of grains per pod were determined by counting the five tagged plants per plot at harvesting. The number of days to 50% flowering and pod formation was recorded. Physiological maturity was determined when the green gram colour changed from green to brown.

Grain yield was evaluated by harvesting all crops within each plot, drying the grain to approximately 12% moisture content and weighing it using a digital balance. The weight of 100 grains was determined by weighing a random sample of 100 harvested grains per plot.

2.4 Statistical Analysis

All data were subjected to analysis of variance (ANOVA) using R software, and treatment means were separated using Tukey's HSD at the 5% ($P \leq 0.05$) level of significance.

3. Results and Discussion

3.1 Effects of Biochar, FYM, and Hydrogel on Soil Moisture Content

Biochar, FYM and Hydrogel significantly ($P \leq 0.05$) influenced soil moisture levels across all research sites and soil depths (Table 1.). Averaged across seasons and sites, soil moisture levels followed the order control < Hydrogel < FYM ≤ biochar. At the 0–20 cm depth, biochar and FYM recorded significantly higher moisture contents than Hydrogel and the control. Similar trends were observed at the 20–40 cm depth. Across the three cropping seasons, biochar consistently recorded the highest soil moisture content at both depths, followed by FYM, Hydrogel and the control, with moisture levels generally increasing gradually from the first to the third season in all treatments. Overall, although the effects of biochar and FYM were not significantly different, biochar, FYM and Hydrogel increased soil moisture by 35%, 33% and 28%, respectively, compared with the control.

Table 1. Effects of soil amendments on soil moisture content (%) at two soil depths in three seasons

	Soil moisture (%)					
	Season One		Season Two		Season Three	
Treatment	**0-20cm**	**20-40cm**	**0-20cm**	**20-40cm**	**0-20cm**	**20-40cm**
Farmyard Manure	4.84b	4.68b	6.06ab	5.91ab	6.52a	6.26ab
Biochar	4.88b	4.74b	6.18a	6.10a	6.63a	6.38a
Hydrogel	4.74c	4.59c	5.84c	5.66c	6.04b	6.12b
Control	4.11d	4.28d	4.28d	4.38c	4.36c	4.41c
CV%	2.5	1.3	1.2	2.3	3.3	2.1
Pr(>F)	0.0056	0.0044	0.0054	0.0036	0.0052	0.0041

Means followed by same letter within a column are not significantly different at P≤ 0.05. Hydrogel-Hydrogel

3.2 Effects of Biochar, FYM, and Hydrogel on Total Soil Nitrogen

Biochar, FYM and Hydrogel significantly ($P \leq 0.05$) influenced total soil nitrogen (TN) levels across the research sites and soil depths (Table 2). Overall, biochar consistently supported the highest TN concentrations, with a 49% increase compared with the control, followed by FYM (36%) and Hydrogel (18%). Averaged across seasons and sites, soil TN levels followed the order control < Hydrogel < FYM ≤ biochar. Nitrogen levels under the biochar and FYM treatments differed only in the topsoil (0–20 cm) depth.

Table 2. Effects of soil amendments on soil total Nitrogen (%) in two soil depths and three cropping seasons

	Season One		Season Two		Season Three	
Treatment	**0-20cm**	**20-40cm**	**0-20cm**	**20-40cm**	**0-20cm**	**20-40cm**
FYM	0.79a	0.67b	0.88a	0.72b	0.82a	0.75b
Biochar	0.81a	0.77a	0.92a	0.79a	0.98a	0.81a
Hydrogel	0.67c	0.66b	0.68b	0.66b	0.69b	0.67b
Control	0.66c	0. 56c	0.65b	0.54c	0.51b	0.49b
CV%	3.4	2.308	5.3	2.12	4.5	2.2
Pr(>F)	0.0444	0.0117	0.0432	0.0317	0.0248	0.0117

Means followed by same letter within a column are not significantly different at P≤ 0.05. Hydrogel-Hydrogel

3.3 Effects of Biochar, FYM, and Hydrogel on Soil Organic Carbon

Biochar, FYM and Hydrogel significantly ($P \leq 0.05$) influenced soil organic carbon (SOC) content across seasons, research sites and soil depths (Table 3 and Fig. 1). Biochar supported the highest SOC concentrations, followed closely by FYM, while the control had the lowest values. Although biochar recorded higher values, SOC under the biochar and FYM treatments was not significantly different at all sites, except at the Msambweni

0–20 cm and Shimba Hills 20–40 cm depths. Overall, biochar, FYM and Hydrogel increased SOC by 34%, 28% and 16%, respectively, compared with the control.

A significant ($P \leq 0.05$) treatment × site interaction was observed in the trials at both soil depths, with SOC levels increasing consistently from season 1 to season 3 under the biochar and FYM treatments.

Table 3. Effects of soil amendments on soil total soil carbon (g kg^{-1}) in two soil depths across four sites

	SITE							
	Msambweni		Matuga		Lunga lunga		Shimba Hills	
Treatment	**0-20cm**	**20-40cm**	**0-20cm**	**20-40cm**	**0-20cm**	**20-40cm**	**0-20cm**	**20-40cm**
FYM	0.58b	0.64a	0.81a	0.65a	0.78b	0.76ab	0.89a	0.73b
Biochar	0.67a	0.65a	0.83a	0.69a	0.81a	0.78a	0.91a	0.79a
Hydrogel	0.54c	0.56b	0.68b	0.58b	0.74b	0.71b	0.77b	0.72c
Control	0.50c	0.50b	0.60c	0.54b	0.63c	0.61c	0.65c	0.54d
CV%	4.1	2.1	4.7	2.3	2.6	2.1	5	4.1
Pr(>F)	0.0056	0.0044	0.0054	0.0036	0.0052	0.0041	0.0053	0.0038

Means followed by same letter within a column are not significantly different at P≤ 0.05; Hydrogel-Hydrogel

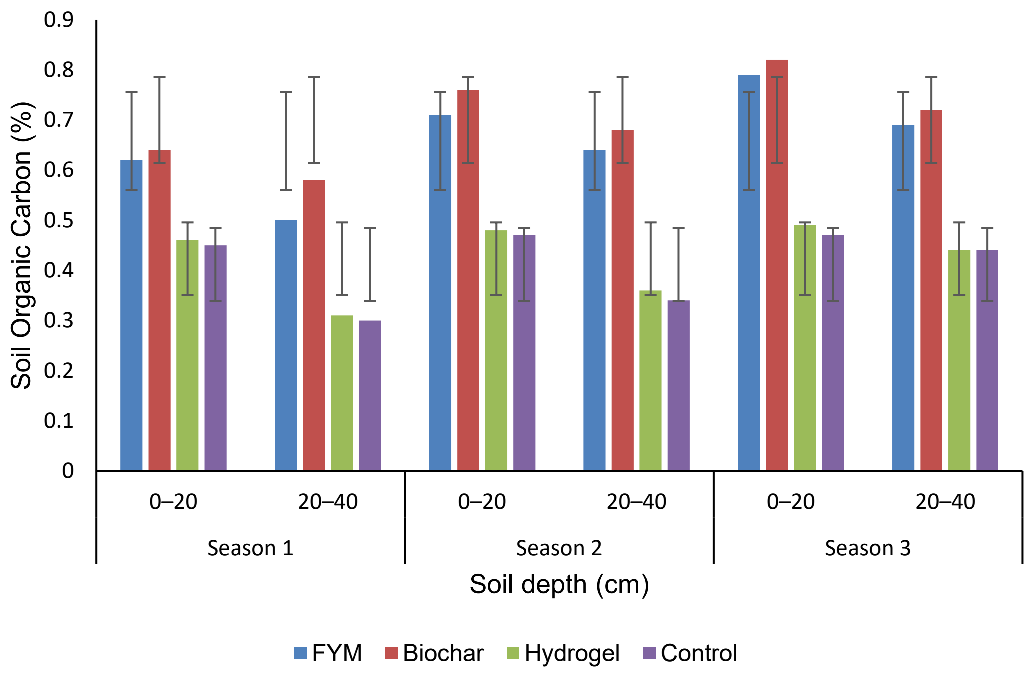

Fig. 1. Effects of soil amendments on soil organic carbon at 0-20 and 20-40cm soil depth across three cropping seasons

3.4 Effects of Biochar, FYM, and Hydrogel on Soil pH

Soil amendments and soil depth significantly affected ($P \leq 0.05$) soil pH levels across all sites and cropping seasons (Table 4 and Fig. 2). Biochar and FYM recorded higher pH levels than Hydrogel and the control, with no significant difference between biochar and FYM. Hydrogel and control values were also not significantly different. Biochar, FYM and Hydrogel increased mean soil pH by approximately 12%, 11% and 1.5%, respectively, at the 0–20 cm depth compared with the control. A similar trend was observed at the 20–40 cm depth, but the values were slightly lower than those in the 0–20 cm layer. Msambweni recorded the highest pH values, while Shimba Hills had the lowest. Soil pH ranged from 5.84 to 6.78, which lies within the moderately acidic to near-neutral range.

Table 4. Effects of soil amendments on soil pH in two soil depths across four sites

	Matuga		Msambweni		Shimba Hills		Lungalunga	
Treatment	**0-20cm**	**20-40cm**	**0-20cm**	**20-40cm**	**0-20cm**	**20-40cm**	**0-20cm**	**20-40cm**
FYM	6.60 a	6.44 a	6.73 a	6.58 a	6.44 a	6.31 a	6.56 a	6.41 a
Biochar	6.78 a	6.64 a	6.91 a	6.77 a	6.61a	6.48 a	6.73 a	6.59 a
Hydrogel	6.22 b	6.08 b	6.35 b	6.20 b	6.06 b	5.93 b	6.17 b	6.02 b
Control	6.13 b	6.09 b	6.34 b	6.11 b	6.02 b	5.84 b	6.08 b	5.93 b
CV (%)	3.2	2.9	3.5	4.1	3.9	3.7	3.8	3.1

Means followed by same letter within a column are not significantly different at P≤ 0.05; Hydrogel-Hydrogel

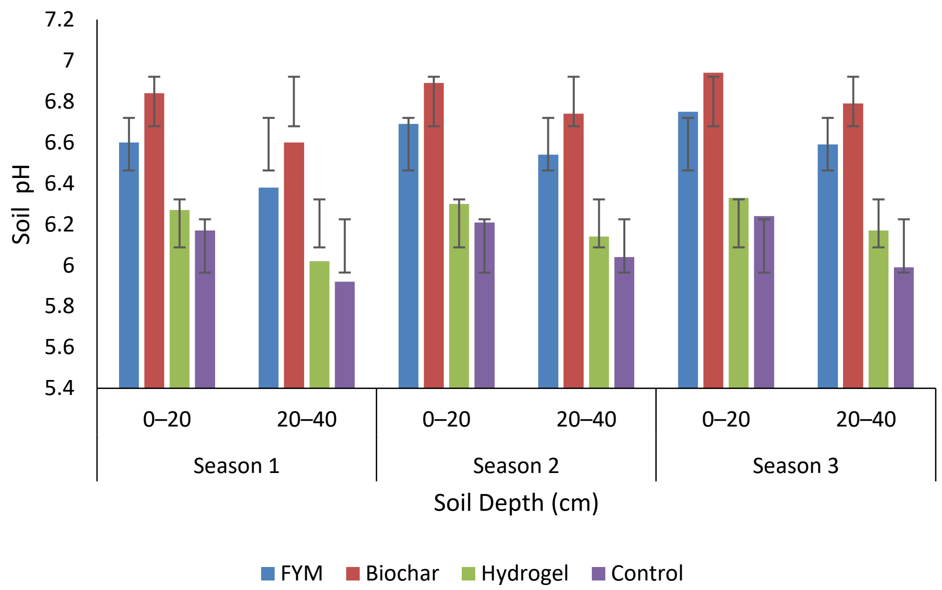

Fig. 2. Effects of soil amendments on soil pH at 0-20 and 20-40cm soil depth across three cropping seasons

3.5 Effects of Biochar, FYM, and Hydrogel on Soil Exchangeable Phosphorus

Exchangeable phosphorus (P) levels differed significantly ($P \leq 0.05$) among treatments, soil depths, sites and cropping seasons (Table 5 and Fig. 3). Biochar and FYM recorded higher P levels than Hydrogel and the control, with no significant difference between biochar and FYM. Hydrogel and control values were also not significantly different. Biochar, FYM and Hydrogel increased mean soil P by approximately 153%, 133% and 13%, respectively, at the 0–20 cm depth compared with the control. A similar trend was observed at the 20–40 cm depth, but the values were slightly lower than those in the 0–20 cm layer. Msambweni had the highest mean P levels, while Shimba Hills had the lowest. In general, all soil P levels in the control and Hydrogel-treated plots were limiting (<10 mg kg^{-1} soil).

Table 5. Effects of soil amendments on soil Exchangeable Phosphorus(mg/kg) in two soil depths across four sites

	Matuga		Msambweni		Shimba Hills		Lungalunga	
Treatment	**0-20cm**	**20-40cm**	**0-20cm**	**20-40cm**	**0-20cm**	**20-40cm**	**0-20cm**	**20-40cm**
FYM	17.6 a	13.7 a	20.4 a	16.1 a	15.7 a	12.4 a	18.2 a	14.2 a
Biochar	19.4 a	15.1 a	22.01 a	17.7 a	17.3 a	13.8 a	20.1 a	15.8 a
HYDROGEL	8.4 b	6.3 b	19.2 b	7.0 b	7.1 b	5.3 b	8.9 b	6.9 b
Control	7.3 b	5.4 b	9.2 b	6.1 b	6.0 b	4.5 b	7.9 b	5.0 b
CV (%)	12.4	3.1	3.4	4.2	3.5	2.1	3	4.4

Means followed by same letter within a column are not significantly different at P≤ 0.05; Hydrogel-Hydrogel

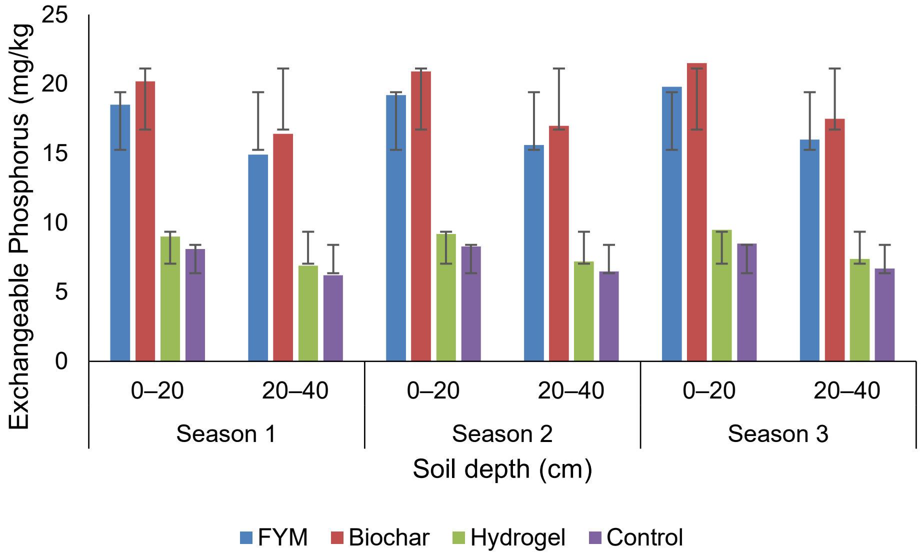

Fig. 3. Effects of soil amendments on exchangeable phosphorus at 0-20 and 20-40cm soil depth across three cropping seasons

3.6 Effects of Biochar, FYM, and Hydrogel on Soil Exchangeable Potassium

Biochar, FYM and Hydrogel significantly influenced ($P \leq 0.05$) exchangeable potassium (K) levels across soil depths, sites and cropping seasons (Table 6 and Fig. 4). Although biochar and FYM recorded higher K levels than Hydrogel and the control across all soil depths, seasons and sites, K levels under the biochar and FYM treatments were not significantly different. Similarly, K values under Hydrogel and the control were not significantly different. Biochar and FYM increased mean soil K by approximately 105%, while Hydrogel increased K by 8% compared with the control. K levels followed a similar trend at the 20–40 cm depth. Comparing the research sites, Msambweni had the highest mean K levels, while Shimba Hills had the lowest.

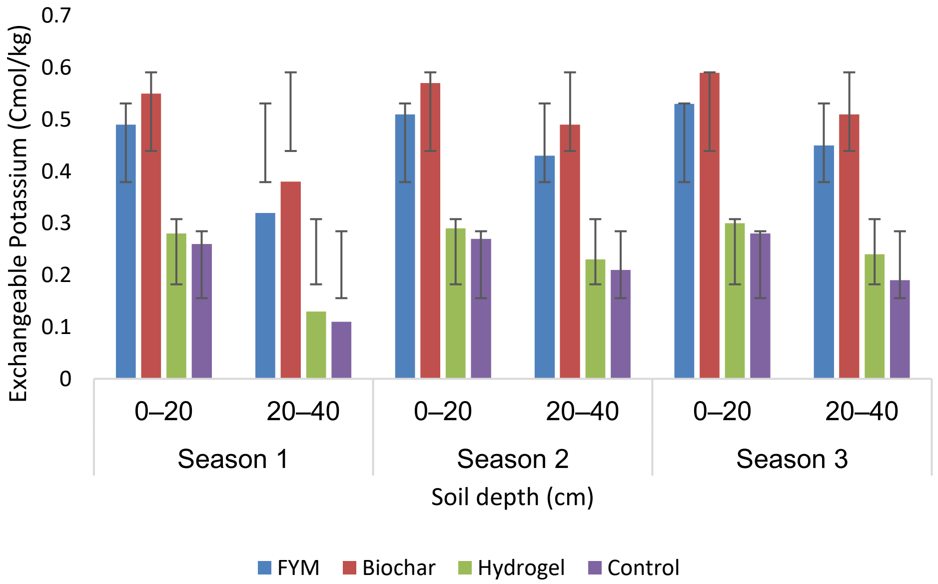

Fig. 4. Effects of soil amendments on exchangeable potassium at 0-20 and 20-40cm soil depth across three cropping seasons

Table 6. Effects of soil amendments on soil total soil Exchangeable Potassium (cmol kg^{-1}) in two soil depths across four sites

	Matuga		Msambweni		Shimba Hills		Lungalunga	
Treatment	**0-20cm**	**20-40cm**	**0-20cm**	**20-40cm**	**0-20cm**	**20-40cm**	**0-20cm**	**20-40cm**
FYM	0.61 a	0.53 a	0.65 a	0.56 a	0.57 a	0.50 a	0.71 a	0.52 a
Biochar	0.67 a	0.59 a	0.71 a	0.62 a	0.63 a	0.55 a	0.77 a	0.58 a
Hydrogel	0.39 b	0.33 b	0.42 b	0.36 b	0.35 b	0.30 b	0.49 b	0.32 b
Control	0.37 b	0.31 b	0.40 b	0.34 b	0.33 b	0.28b	0.47 b	0.30 b
CV (%)	8.5	7.9	8.1	7.6	9	8.3	8.4	7.8

Means followed by same letter within a column are not significantly different at P≤ 0.05; Hydrogel-Hydrogel

3.7 Effects of Biochar, FYM, and Hydrogel on Soil Exchangeable Sulphur

Biochar, FYM and Hydrogel significantly influenced (P ≤ 0.05) exchangeable sulphur (S) levels across soil depths, sites and cropping seasons (Table 7 and Fig. 5). Although biochar and FYM recorded higher S levels than Hydrogel and the control across soil depths, seasons and sites, S levels supported by the biochar and FYM treatments were not significantly different. Similarly, S levels under Hydrogel and the control were not significantly different. Biochar and FYM increased mean soil S by approximately 122%, while Hydrogel increased S by 6% compared with the control. Although S levels at the 20–40 cm depth were lower than those at the 0–20 cm depth, treatment effects followed a similar trend, with biochar leading and the control recording the lowest values. Comparing the research sites, Msambweni had the highest mean sulphur levels, while Shimba Hills had the lowest.

Table 7. Effects of soil amendments on soil total soil exchangeable Sulphur (mg kg^{-1}) in two soil depths across four sites

Treatment	**Matuga**		**Msambweni**		**Shimba Hills**		**Lungalunga**	
	0-20cm	**20-40cm**	**0-20cm**	**20-40cm**	**0-20cm**	**20-40cm**	**0-20cm**	**20-40cm**
FYM	13.1 a	11.7 a	14.5 a	12.8 a	12.0a	10.5 a	12.9 a	11.4 a
Biochar	13.9 a	12.5 a	15.3 a	13.6 a	12.7 a	11.2 a	13.6 a	12.0 a
Hydrohel	6.0 b	5.1 b	6.7 b	5.6 b	5.3 b	4.4 b	5.8 b	4.9 b
Control	5.7 b	4.8 b	6.3 b	5.3 b	5.0 b	4.1 b	5.5 b	4.6 b
CV (%)	11.6	10.9	11.2	10.5	12.1	11.4	11.4	10.8

Means followed by same letter within a column are not significantly different at P≤ 0.05; Hydrogel-Hydrogel

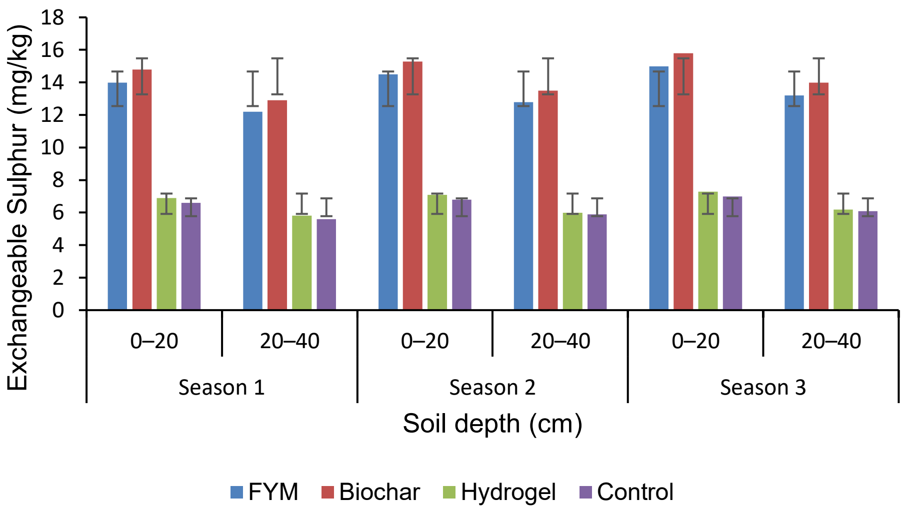

Fig. 5. Effects of soil amendments on exchangeable Sulphur at 0-20 and 20-40cm soil depth across three cropping seasons

3.8 Effects of Biochar, FYM, and Hydrogel on Plant Height

Plant height was significantly ($P \leq 0.05$) affected by site, season and amendment (Table 8). Averaged across sites, crop height followed the order control ≤ Hydrogel ≤ FYM < biochar. Seasonal assessment showed similar trends, with biochar producing the tallest plants and the control producing the shortest plants across the three cropping seasons. However, there was no significant difference between Hydrogel and the control with respect to plant height.

Table 8. Effects of soil amendments on average green gram plant height (cm) in four sites and three cropping seasons

Treatment	Msambweni	Matuga	Lunga lunga	Shimbahills	Season 1	Season 2	Season 3
FYM	48b	55b	54b	54b	53b	51b	53b
Biochar	52a	58a	58a	57a	56a	55a	59a
Hydrogel	44c	48c	48c	50c	48cd	49cb	52c
Control	43c	47cd	46d	47d	46d	48d	50c
CV%	4.1	4.7	2.6	5	20.18	21.19	22.17
Pr(>F)	0.0056	0.0054	0.0052	0.0053	0.004	0.003	0.002

Means followed by same letter within a column are not significantly different at P≤ 0.05; Hydrogel-Hydrogel

3.9 Effects of Biochar, FYM, and Hydrogel on Grain Yield

Biochar, FYM and Hydrogel significantly ($P \leq 0.05$) influenced green gram grain yield across all research sites and seasons (Table 9). Biochar supported the highest grain yield at all sites, ranging from 1.6 to 2.0 t ha^{-1}, followed by FYM (1.5–1.9 t ha^{-1}), Hydrogel (1.2–1.8 t ha^{-1}) and the control (1.1–1.4 t ha^{-1}), which had the lowest yield. Overall, although grain yield under biochar and FYM was not significantly different, biochar, FYM and Hydrogel increased grain yield by 43%, 36% and 20%, respectively, compared with the control.

Table 9. Effects of soil amendments on green gram grain yield (t/ha) in three cropping seasons and four sites

	SITE				SEASON		
Treatment	**Msambweni**	**Matuga**	**Lunga lunga**	**Shimbahills**	**Season 1**	**Season 2**	**Season 3**
FYM	1.66b	1.52ab	1.94ab	1.8b	1.80a	1.80a	1.90a
Biochar	1.80a	1.60a	2.0a	1.90a	1.90a	1.90a	2.00a
Hydrogel	1.4c	1.2c	1.8c	1.7c	1.60b	1.60b	1.70b
Control	1.2d	1.1d	1.4d	1.4d	1.40c	1.50c	1.50c
CV%	5.5	5.1	5.3	5.3	4.2	4.8	4.4
Pr>F	0.015	0.012	0.011	0.011	0.045	0.038	0.031

Means followed by same letter within a column are not significantly different at P≤ 0.05; t/ha- tonnes/ Hectare; Hydrogel-Hydrogel

4. Discussion

Biochar and FYM significantly increased soil moisture content across all sites and cropping seasons. The observed increase in soil moisture content after biochar and FYM application indicates the positive role of organic amendments in improving the moisture-retention capacity of agricultural soils, as well as the cumulative effects of continuous organic amendment application. This moisture-retention capacity can be attributed to biochar's porous structure, well-developed pore network and large surface area, which enhance water adsorption and storage, minimise evaporative losses and ensure water availability for crop uptake (Blanco-Canqui, 2020; H. Jia et al., 2025; Zhu et al., 2025; Sharma et al., 2026). Conversely, farmyard manure (FYM) has been documented to improve soil physical attributes such as porosity, aggregate stability and temperature regulation, leading to increased moisture-retention capacity (Brady & Weil, 2016; Muindi et al., 2019; Rewe et al., 2021; Rizwan et al., 2025). These findings agree with Lustosa Carvalho et al., (2020) and Lustosa Carvalho et al., (2020), who reported enhanced soil moisture-holding capacity after biochar application in tropical soils.

Biochar and FYM significantly increased total nitrogen levels compared with the other treatments. The high total soil nitrogen in the biochar and FYM treatments indicates improved nutrient cycling and retention capacity attributable to either reduced losses or increased microbial activity. According to Lehmann et al., (2011) and Xiao et al., (2026), biochar improves nutrient cycling through increased cation exchange capacity, improved nutrient adsorption and the creation of a favourable environment for microbial activity. Farmyard manure, on the other hand, improves soil nitrogen pools by creating favourable conditions for organic matter decomposition, mineralisation and nutrient retention (Marschner, 2012; Rewe et al., 2022; Muchomba et al., 2023b; Musa et al., 2026; Xing et al., 2025). Similar improvements in soil nitrogen after biochar and/or organic manure application have been reported by Agegnehu et al., (2016), Nain et al., (2024), Muindi et al., (2022), Enock et al., (2023), Rizwan et al., (2025) and M. Zhang et al., (2025).

Biochar and FYM significantly improved SOC levels throughout the cropping period. The continuous increase in SOC after biochar and FYM application can be largely attributed to improved carbon sequestration and stabilisation. Biochar contains an intractable carbon fraction that is resistant to microbial decomposition and can remain stable in soil for extended periods (Lehmann et al., 2011; Yu et al., 2026). Farmyard manure adds labile organic matter to the soil, stimulating microbial activity and carbon accumulation (Brady & Weil, 2016). These findings are consistent with Shao et al., (2023), Kazungu et al., (2023), Ashraf et al., (2023), Machado et al., (2026) and Xiao et al., (2026), who reported significant increases in soil carbon levels after biochar and/or manure application.

Both biochar and FYM increased soil pH, exchangeable phosphorus, potassium and sulphur across all research sites, seasons and soil depths compared with Hydrogel and the control treatments. The observed increases in pH, phosphorus, potassium and sulphur after biochar and FYM application can be attributed to improved surface functional groups, microbial activity, mineralisation, soil reaction and reduced P adsorption due to proton consumption during decomposition, leading to increased availability of nutrients such as phosphorus, sulphur and base cations within the exchange complex (Muindi et al., 2014; Brady & Weil, 2016; Muindi, 2019; Esilaba et al., 2023; M. Zhang et al., 2025). These findings agree with those of Kisinyo et al., (2019) and Njogo et al., (2018), who reported significant increases in pH and soil P after FYM application. Similarly, Majengo et al., (2025) reported increased soil phosphorus and pH following biochar application in western Kenya, while Laird et al., (2010) reported increased soil sulphur levels after biochar application in Midwestern agricultural soils.

Biochar supported the greatest plant height and grain yield, followed by farmyard manure, while Hydrogel and the control did not differ significantly in their effects on plant height and grain yield. The significant increases in plant height and grain yield under biochar and FYM can be attributed to their ability to enhance water and nutrient retention, leading to improved root development, nutrient availability, uptake, photosynthetic efficiency, growth and grain yield (Steiner et al., 2007; Agegnehu et al., 2015; Muti et al., 2017). Similar crop growth and yield increases in biochar-amended soils have been reported by Kiprotich et al., (2022), Okine et al., (2026) and Xiao et al., (2026). Crop growth and yield increases following farmyard manure application have also been reported by Muchomba et al. (2023b), Li et al., (2024) and Mwakidoshi et al., (2026).

5. Conclusion

This study showed that biochar and farmyard manure improved soil fertility, soil moisture retention, green gram growth and grain yield under smallholder farming conditions in Kwale County. Across the study sites and cropping seasons, both amendments consistently produced higher values for soil moisture, soil organic carbon, total nitrogen, soil pH, exchangeable phosphorus, potassium and sulphur than the untreated control. These improvements were associated with better crop growth and increased grain yield. Biochar produced the highest overall response, although its effects were often not significantly different from those of farmyard manure for several measured soil and crop parameters. Hydrogel also improved some measured parameters, particularly soil moisture and grain yield, but its effects were generally smaller than those recorded under biochar and farmyard manure. In several cases, Hydrogel did not differ significantly from the control, indicating limited performance under the tested conditions compared with organic amendments. Overall, the results suggest that biochar and farmyard manure can contribute to improved soil health and green gram productivity in coastal sandy soils. Further work is needed to refine application rates, assess economic viability and determine the longer-term effects of these amendments across different agroecological conditions.

6. Limitations

This study was conducted under farmer-managed conditions in four sub-counties of Kwale County and therefore reflects the soil and management conditions of the selected coastal sites. The findings may not be directly transferable to other agroecological zones without further validation. The experiment evaluated single application rates and did not assess amendment combinations or a wider range of rates. A detailed economic analysis was also not included, and the amendment properties were not fully described. Longer-term monitoring is required to determine the persistence of soil fertility changes and residual effects.

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Declaration of AI Use

This manuscript was prepared through the combined contributions of all author(s), including contributions to the study design, data, content development, results, interpretation, and related scholarly work. The author(s) acknowledge the use of Grammarly and ChatGPT to assist with grammar checking, language refinement, reference formatting. These AI-assisted tools were not used as authors and did not replace the intellectual contributions or scholarly judgment of the author(s). All AI-assisted outputs, including content, references, and interpretations, were carefully reviewed, revised, verified, and approved by the author(s). The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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